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Dynamics of Shape Memory Alloy Systems, Phase 2

Marcelo Savi
FUNDACAO COORDENACAO DE PROJETOS PESQUISAS E EEUDOS TECNOL

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14. ABSTRACT

This research project has the objective to investigate nonlinear dynamics and chaos in shape memory alloy (SMA) systems. This subject is scientific relevant due to numerous aspects. Among them, it is important to mention the complex thermomechanical behavior of SMA and the rich dynamics due to strong nonlinearities of systems with SMA elements. Besides this scientific relevance, SMAs have an increasing technological interest being related to several applications including aerospace and oil industries, robotics and bioengineering devices. Therefore, the present project has expected impacts in several fields of science and engineering. The international cooperation between the Federal University of Rio de Janeiro (UFRJ) and Texas A&M University (TAMU) is important to be highlighted.

15. SUBJECT TERMS

Nonlinear dynamics; smart material systems; shape memory alloys.

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1 - INTRODUCTION

The development of the research Project successfully achieves expectations, generating important results from different approaches. In this regard, it is important to highlight joint publications of sub-project participants, showing the mature level of the research. This is due to a strong interaction among different Brazilian Universities (UFRJ, CEFET/RJ, UnB, UFU and UFF) and also among foreign Universities (Texas A&M University, University of Aberdeen, Technological University of Denmark and Dalhousie University). This report highlights the main results of this research effort that includes constitutive modeling, nonlinear dynamics and control of shape memory alloy systems.

2 – PUBLICATIONS

JOURNAL PAPERS – STRICT RELATED TO THE PROJECT

1. **"Synergistic Use of Smart Materials for Vibration-Based Energy Harvesting"**, L.L. Silva, S.A. Oliveira, P.M.C.L. Pacheco & M.A. Savi, ***European Physical Journal – Special Topics***. 2015. *ISSN 1951-6355*.

2. **"Experimental Analyses of Dynamical Systems Involving Shape Memory Alloys"**, S. Enemark, M.A. Savi & I.F. Santos, ***Smart Structures and Systems***, v.15, n.6, pp.1521-1542, 2015. *ISSN 1738-1584*. doi: 10.12989/sss.2015.15.6.1521.

3. **"Nonlinear Dynamics and Chaos of Shape Memory Alloy Systems"**, M.A. Savi, ***International Journal of Non-linear Mechanics***, v.70, pp.2-19, 2015. *ISSN 0020-7462*. doi:10.1016/j.ijnonlinmec.2014.06.001

4. **“Nonlinear Geometric Influence on the Mechanical Behavior of Shape Memory Alloy Helical Spring”**, M.A. Savi, P.M.C.L. Pacheco, M.S. Garcia, R.A.A. Aguiar, L.F.G. Souza & R.B. da Hora, ***Smart Materials and Structures***, v.24, n.3, 2015, Article 0350122015. *ISSN 0964-1726*. doi:10.1088/0964-1726/24/3/035012.

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11. **“Shape Memory Alloy Helical Springs Performance: Modeling and Experimental Analysis”**, R.A.A. Aguiar, W. C. C. Leão Neto, M.A. Savi & P.M.C.L. Pacheco, ***Materials Science Forum***, v.758, pp.147-156, 2013. *ISSN 0255-5476*. doi:10.4028/www.scientific.net/MSF.758.147

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16. **"Chaos Control Applied to Piezoelectric Vibration-Based Energy Harvesting Systems"**, W.O.V. Barbosa, A.S. de Paula, M.A. Savi & D.J. Inman, ***European Physical Journal – Special Topics***, 2015. *ISSN 1951-6355*.

17. **"Experimental Bifurcation Control of a Parametric Pendulum"**, A.S. de Paula, M.A. Savi, S. Vahid Vaziri H., E. Pavlovskaia & M. Wiercigroch, ***Journal of Vibration and Control***. *ISSN 1077-5463.*

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33. **"Bifurcation Control of a Parametric Pendulum"**, A.S. de Paula, M.A. Savi, M. Wiercigroch & E. Pavlovskaia, ***International Journal of Bifurcation and Chaos***, v.22, n.5, Article 1250111, pp.1-14, 2012. *ISSN 0218-1274*. doi:10.1142/S0218127412501118

34. **"Chaos Control Applied to Mechanical Systems"**, A.S. de Paula & M.A. Savi, ***Chaotic Modeling and Simulation - International Journal of Nonlinear Science***, v.1, n.1, pp.17-24, 2012. *ISSN 2241-0503*.

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37. **“Analytical and Numerical Analysis of 3D Grid-Reinforced Orthotropic Composite Structures”**, E.M. Hassan, A.V. Georgiades, M.A. Savi & A.L. Kalamkarov, ***International Journal of Engineering Science***, v.49, n.7, pp.589-605, 2011. *ISSN 0020-7225*. doi:10.1016/j.ijengsci.2011.02.004

3 – CONSTITUTIVE MODELING

Despite numerous applications of SMAs (Machado & Savi, 2003, 2002; Paiva & Savi, 2006), constitutive theories used to describe their thermomechanical behavior are still not able to describe all alloy characteristics. This research, make an effort to explore constitutive models, proposing an alternative model.

This research has the participation of the following researchers: *Prof. P. Pacheco (CEFET/RJ)*, *Prof. Theodoro Antoun Netto (COPPE/UFRJ)*, *Prof. A. Paiva (UFF)*, *Dr. P.C.C. Monteiro Jr. (COPPE/UFRJ)*, *Dr. L.G. Machado (Texas A&M University)*, and the students: *S. A. Oliveira*, *V. Souza* and *V. Dornelas*. It is also important to highlight the participation of ***Prof. Alexander Kalamkarov (Dalhousie University – Canada)***. The main results were published in conferences *COBEM 2009*, *CONEM 2008, COBEM 2007, McMat 2007* and in journals: *International Journal of Solids and Structures, Archive of Applied Mechanics, Mechanics Research Communications, Journal of Intelligent Material Systems and Structures* and *Smart Materials and Structures*.

The proposed model allows the description of different aspects related to thermomechanical behavior of SMAs, being flexible (Paiva *et al.*, 2005a,b, Paiva & Savi, 2006; Savi & Paiva, 2005; Baêta-Neves *et al.*, 2004; Savi *et al.*, 2002a). In brief, the model considers four macroscopic phases: an austenite and three martensitic variants (*M*, *M*+ and *M*−), respectively representing temperature induced martensite and stress-induced related to tensile and compressive behavior, respectively.

The model is developed within the framework of generalized standard materials in such a way that the model is thermodynamically consistent. The model also includes plasticity, thermal expansion, and transformation induced plasticity (TRIP) and there are coupling among these

phenomena. Proper constraints are employed in order to describe internal subloops due to incomplete phase transformation that is a relevant point.

This novel model shows to be capable to represent different aspects of SMAs, presenting coherent results. Figure 1 shows the pseudoelastic effect of NiTi alloy comparing numerical and experimental results. The shape memory effect is shown in Figure 2, while Figure 3 shows the two way shape memory alloy due the thermo-plastic-phase transformation coupling, which is na important contribution of this research.

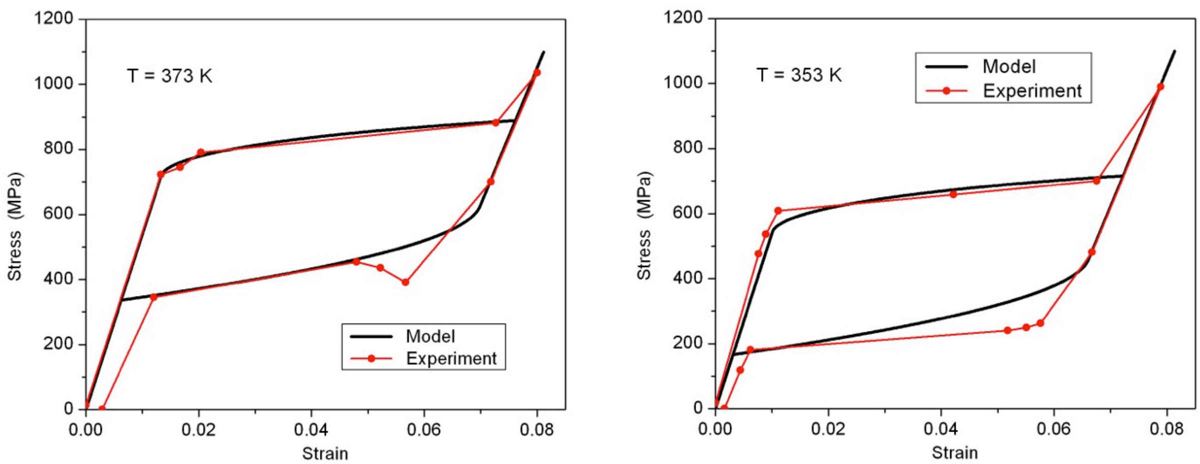


Figure 1 – Pseudoelastic effect.

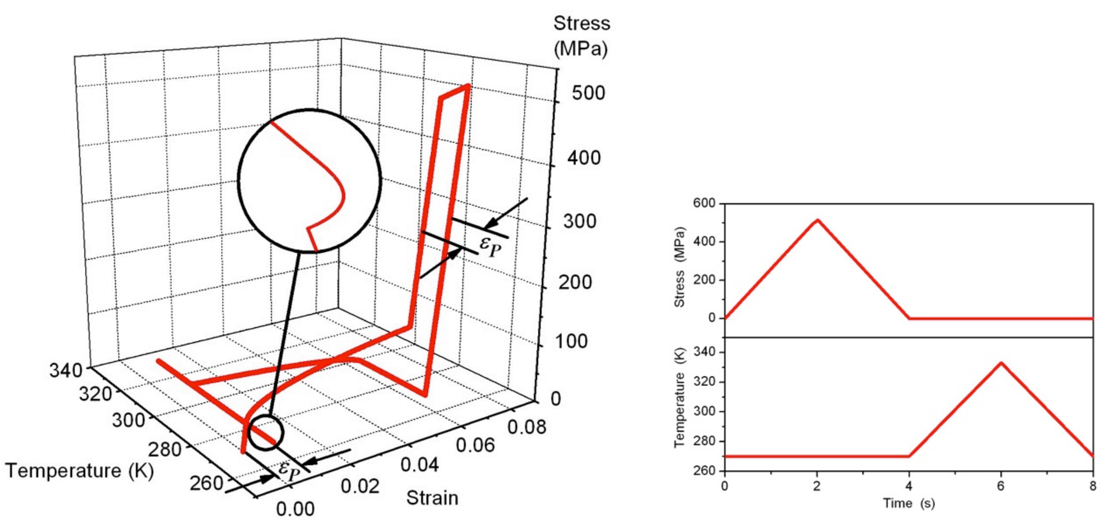


Figure 2 – Shape memory effect.

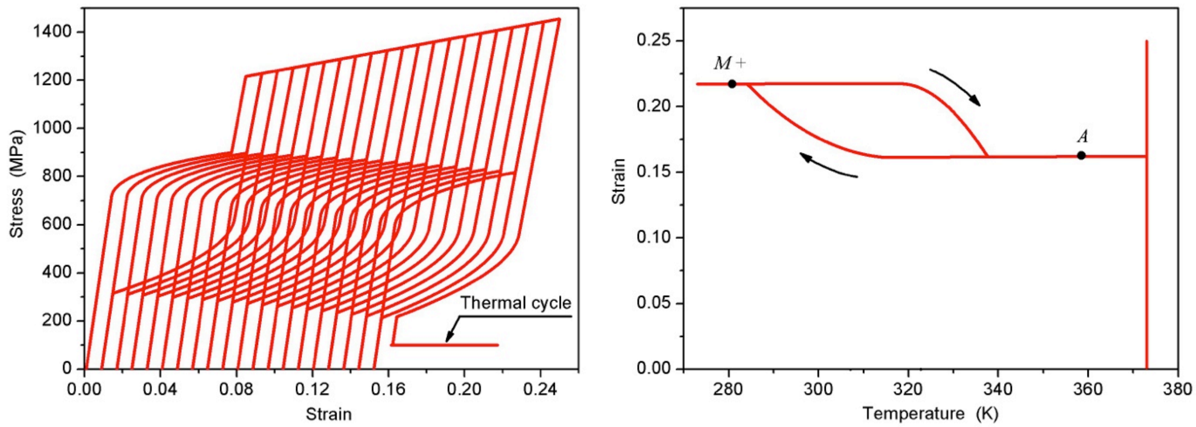


Figure 3 – Two way shape memory effect.

Internal subloops due to incomplete phase transformations are shown in Figure 4, together with experimental data. On the other hand, Figure 5 shows the TRIP effect.

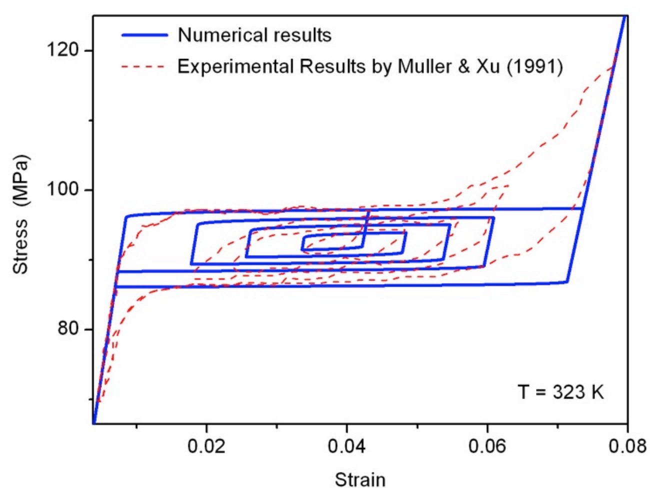


Figure 4 – Subloops.

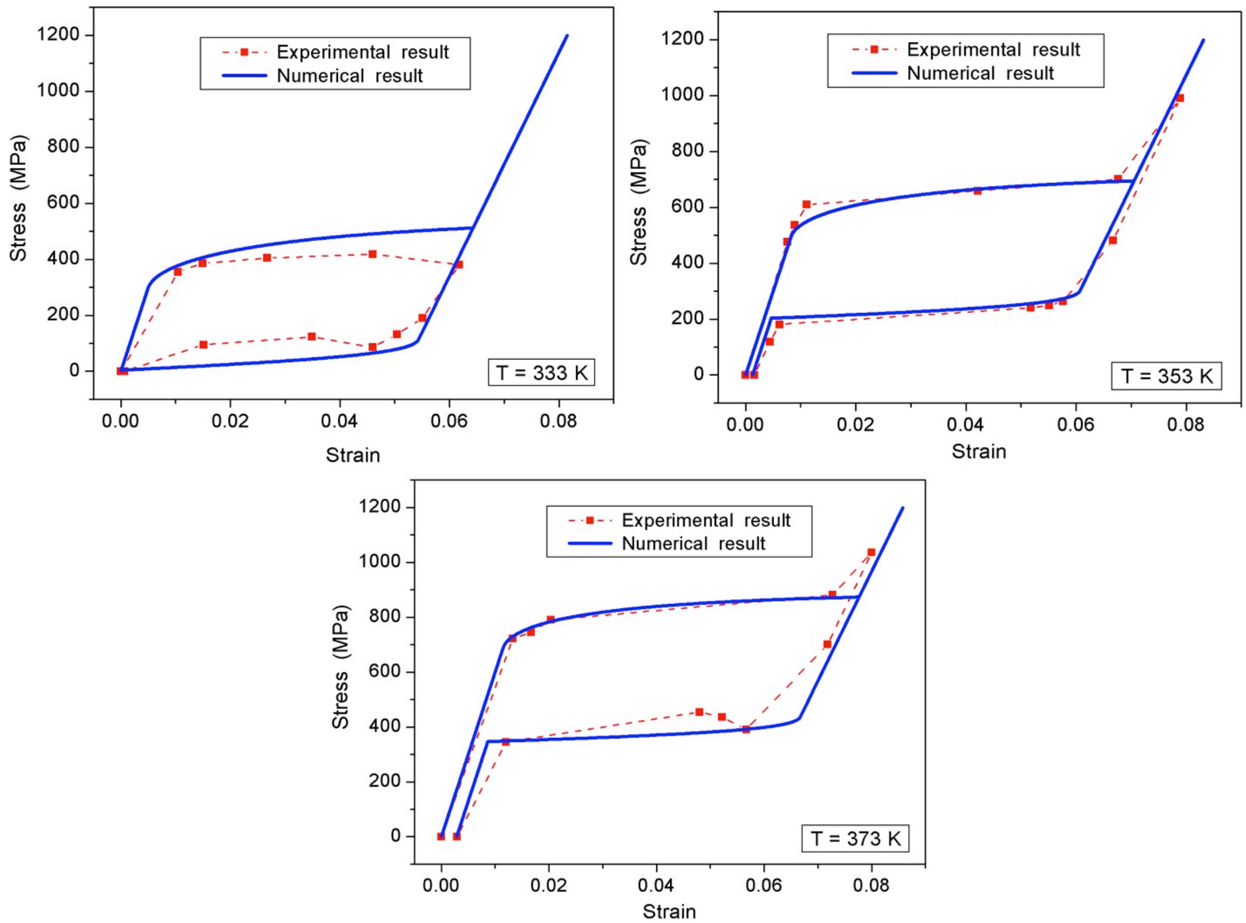


Figure 5 – TRIP.

Besides all these aspects, the thermomechanical coupling is also of concern. This is essential for the comprehension of rate dependence behavior of SMAs. Figure 6 shows some results comparing numerical and experimental tests.

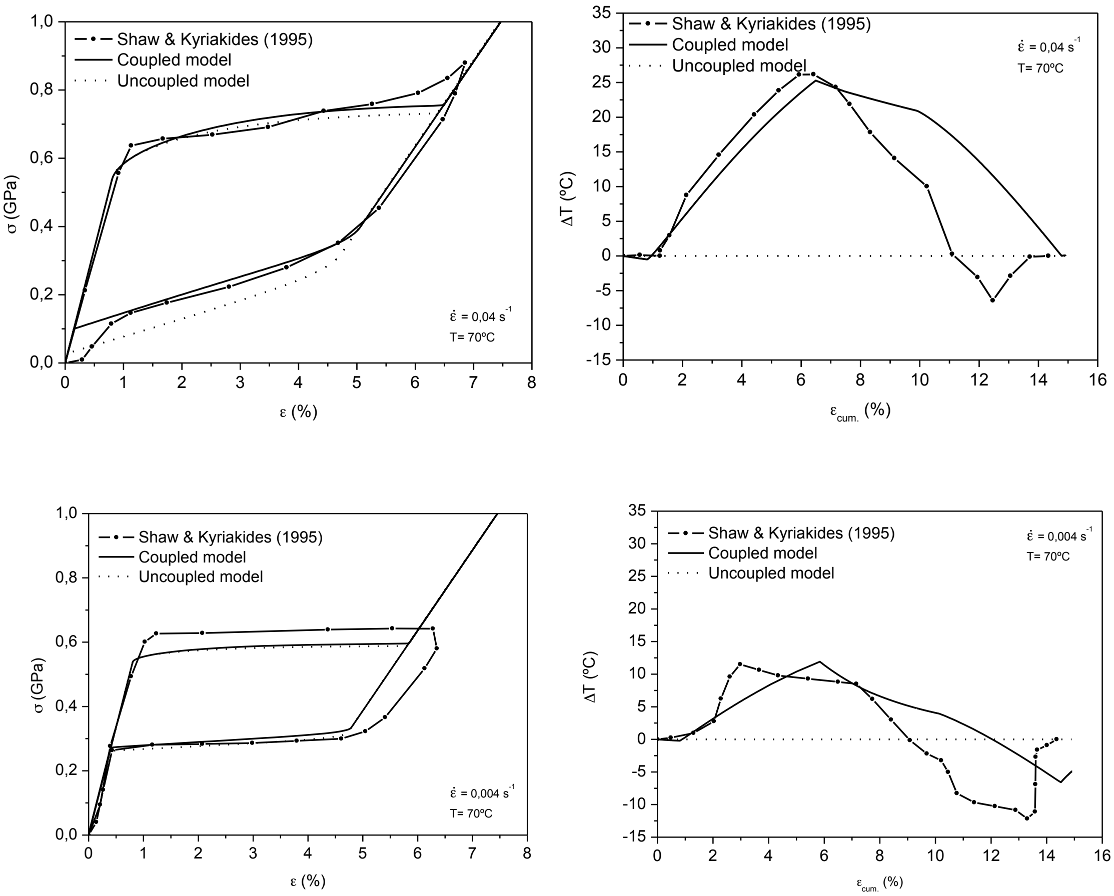


Figure 6 – Thermomechanical coupling.

Afterward, we start develop a three-dimensional version of the model (Oliveira *et al.*, 2010). The idea is to develop a model inspired on the 1D model using a equivalent strain measure, called inductor, described as follows:

$$\Gamma = \frac{1}{3}\varepsilon_{kk}^{e} + \frac{2}{3}\left|\sqrt{3J_2^e}\right| \operatorname{sign}(\varepsilon_{kk}^{e})$$

It is important to note that this inductor is influenced by either volumetric or deviatoric effects and allows the use of the same volume fractions of the 1D model. Figure 7 presents a result for a tension-torsion coupled test.

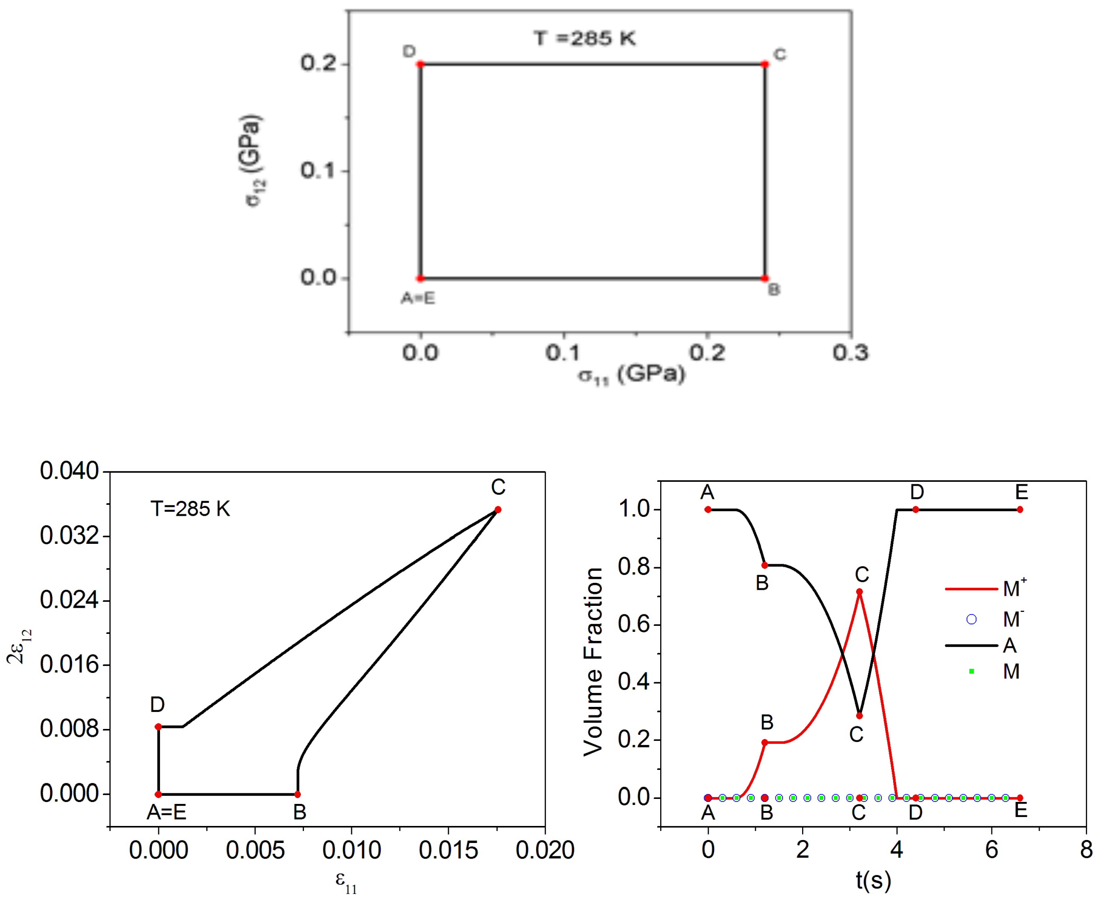


Figure 7 – Tension-torsion coupled test: strain curves.

4 – SMA CHARACTERIZATION

The three-dimensional modeling of SMAs allows one to describe several actuators. A helical spring is one of these possibilities vastly employed in several applications. This research has the participation of the following researchers: *Prof. P. Pacheco (CEFET/RJ)*, *Prof. R. Aguiar (CEFET/RJ)* and S. Oliveira (PhD student). The main results were published in conferences *COBEM 2009*, *CONEM 2010, COBEM 2011, CONEM 2012* and in journals: *International*

Journal of Solids and Structures, Archive of Applied Mechanics, Journal of Intelligent Material Systems and Structures, Smart Materials and Structures and *Material Science Forum*.

Experimental tests were performed with the apparatus shown in Figure 8 and Figure 9 shows force-displacement curves for different temperatures, applied by electric current.

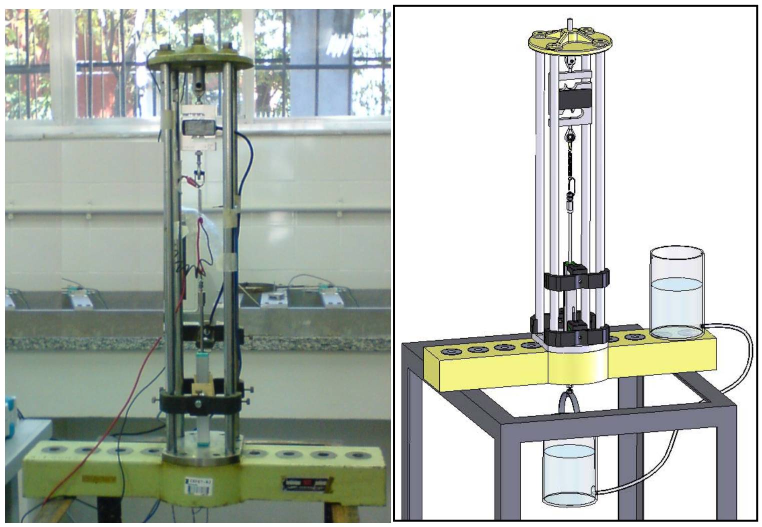


Figure 8 – Experimental set up.

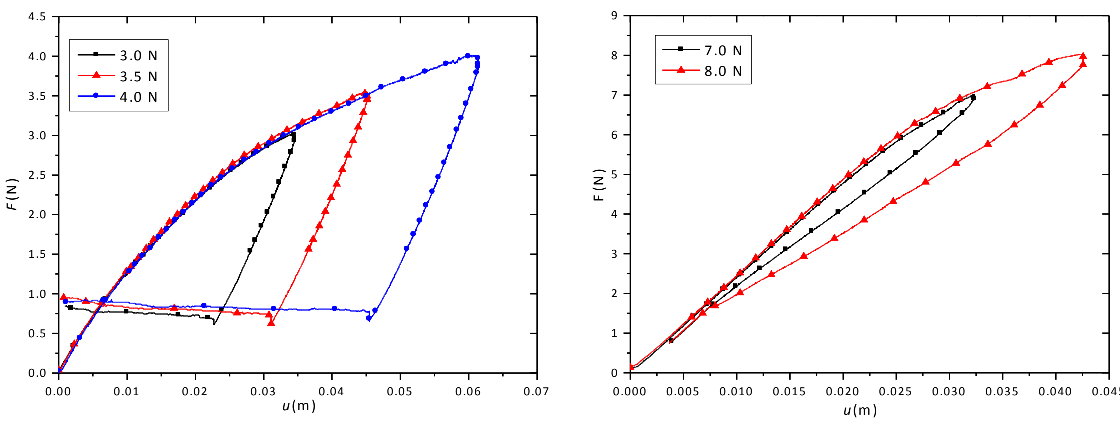


Figure 3 – Force-displacement curves for SMA springs.

The three-dimensional constitutive model can be reduced to simpler situations. A interesting possibility is the description of spring behavior. Figures 4 and 5 show a comparison between numerical and experimental tests for shape memory and pseudoelastic effects. For more details, see Aguiar *et al.* (2010).

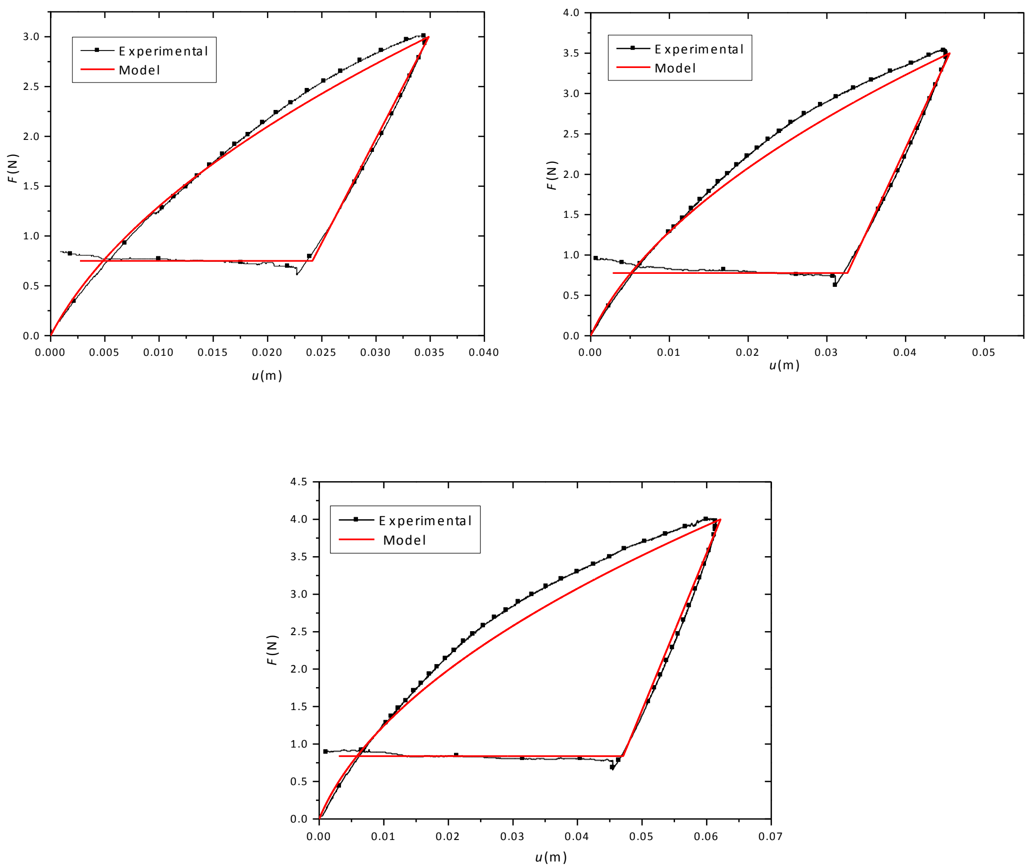


Figure 4 – Shape memory effect.

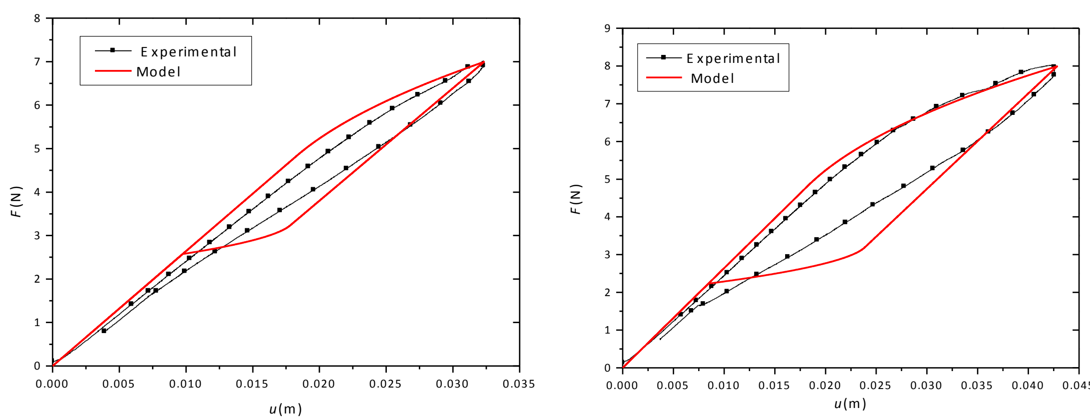


Figure 5 – Pseudoelastic effect.

5 – NONLINEAR DYNAMICS

Smart material systems have an increasing importance on mechanical sciences and engineering. Robotics, aerospace systems, bioengineering are some examples where smart materials are employed. In this regard, shape memory alloys are of special interest when large forces/displacements are needed (Machado & Savi, 2003, 2002, Paiva & Savi, 2006). This Project dedicated a special effort to analyze several aspects related to nonlinear dynamics of shape memory alloy systems. This research has the participation of the following researchers: *Prof. P. Pacheco (CEFET/RJ)*, *Prof. R. Aguiar (CEFET/RJ)*, and the students *S. Oliveira, S. Enemark, A. Carvalho*. It should also be highlighted the participation of *Prof. D. Lagoudas (Texas A&M University)* and *Prof. I. Santos (DTU)*. The main results were published in conferences *COBEM 2009*, *CONEM 2010, COBEM 2011, CONEM 2012* and in journals: *Journal of Intelligent Material Systems and Structures, Smart Materials and Structures* and *Material Science Forum, Chaos Solitons and Fractals*.

Initially, numerical investigation was carried out. One-degree of freedom system presents a very rich response characterized by different kinds of responses including chaos. Mutistability is another interesting characteristic related to the SMA system dynamics. Moreover, temperature plays an essential role in system dynamics being the driving force for some adaptive behavior of these systems. Another important aspect that is of special interest for dynamical applications is the adaptive dissipation due to hysteretic behavior. Since hysteresis is temperature dependent it is possible to adjust its position, changing the dissipation capacity. Besides, this dissipation depends on the system amplitude.

An important contribution of this project to this subject is a procedure to evaluate Lyapunov exponents for hysteretic systems (Machado *et al.*, 2009). This procedure considers the classical algorithm due to Wolf *et al.* (1995) but considering a state space split. The hysteretic behavior is treated as an equivalent linear viscous damping for exponent estimation purposes.

Vibration reduction is of special interest in engineering applications. In this regard, SMAs are employed in two distinct ways: high dissipation capacity due to hysteresis; property changes due to phase transformations. Figure 6 shows a typical application of SMA system employed to

avoid critical resonant conditions. Note that, hysteretic dissipation avoids the amplitude increase due to resonant conditions.

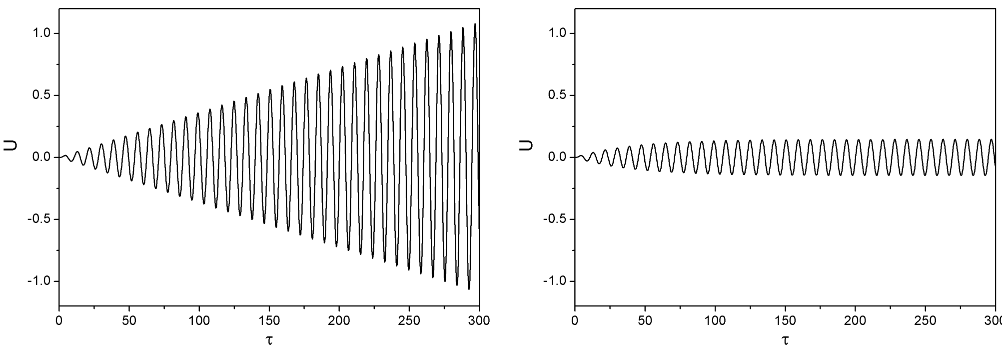


Figure 6 – Resonant conditions: comparison between elastic (left) and SMA (right) systems.

The temperature dependence provides important characteristic to the system. One of those is the possibility to design adaptive tuned vibration absorbers. Figure 7 presents this idea showing how it is possible to change absorber characteristics by changing the temperature. All details of this analysis can be found in a paper published in the *Journal of Intelligent Material Systems and Structures* (Savi *et al.*, 2011).

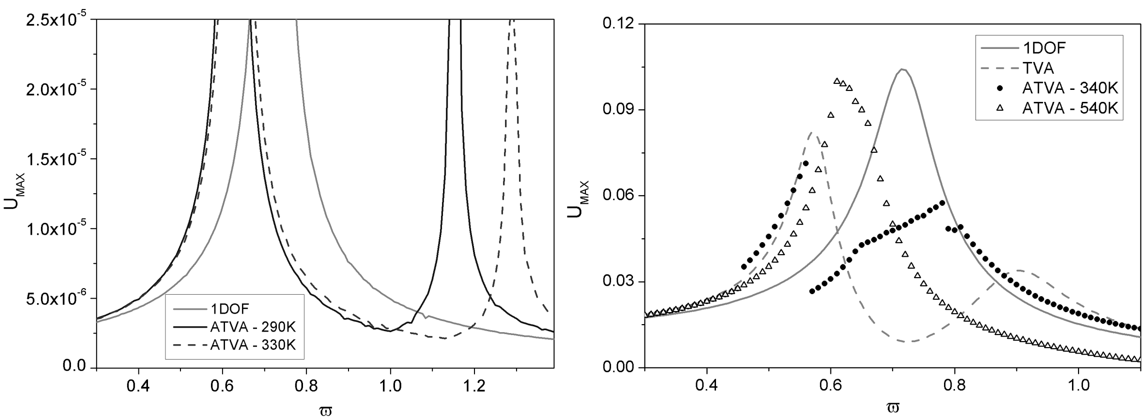


Figure 7 – Adaptive tuned vibration absorber with SMA elements.

This idea was experimentally investigated by considering an oscillator apparatus presented in Figure 8. Results confirm the possibilities presented in numerical simulations. Figure 9 shows the vibration reduction caused by temperature changes.

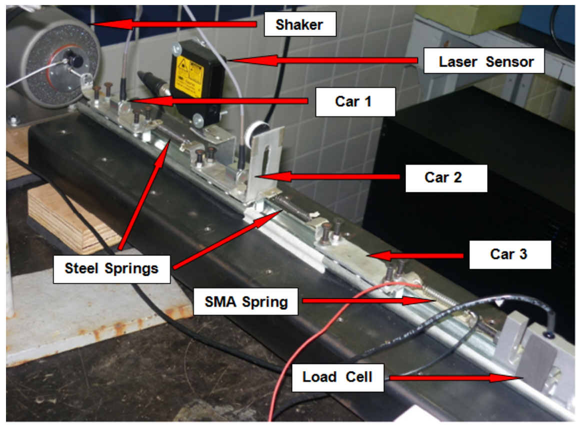


Figure 8 – Experimental apparatus of an SMA oscillator.

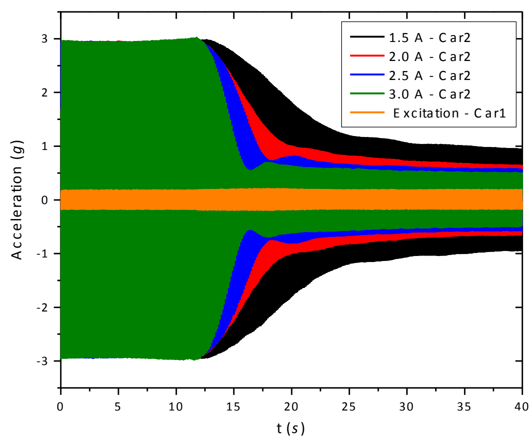


Figure 9 – Vibration reduction caused by temperature changes.

Impact system is another interesting approach to the use of SMAs for vibration reduction purposes. This idea is applicable in different situations including rotordynamic systems. Figure 10 shows a one-dimensional prototype of this system. *Prof. M. Wiercigroch*, *Prof. E. Pavlovskaia*, *Dr. E. Sitnikova* and *B. Santos* worked on this Project and results were published in *Chaos, Solitons & Fractals* (Santos & Savi, 2009) and *International Journal of Non-linear Mechanics* (Sitnikova *et al.*, 2010). It is important to note that SMA dissipation change the

system dynamics, presenting less complex behaviors as shown in Figures 11 and 12. An important application of this idea is on rotordynamic systems where impacts between the rotor and the bearing can be used to dissipate energy. A sketch of this system is presented in Figure 13.

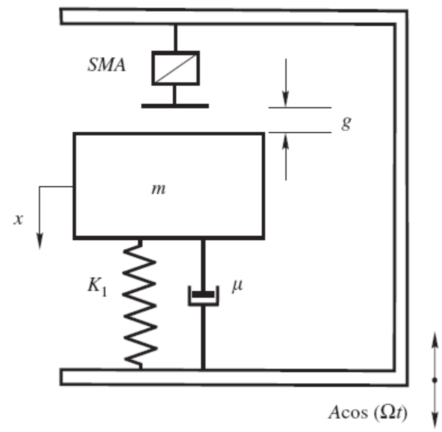
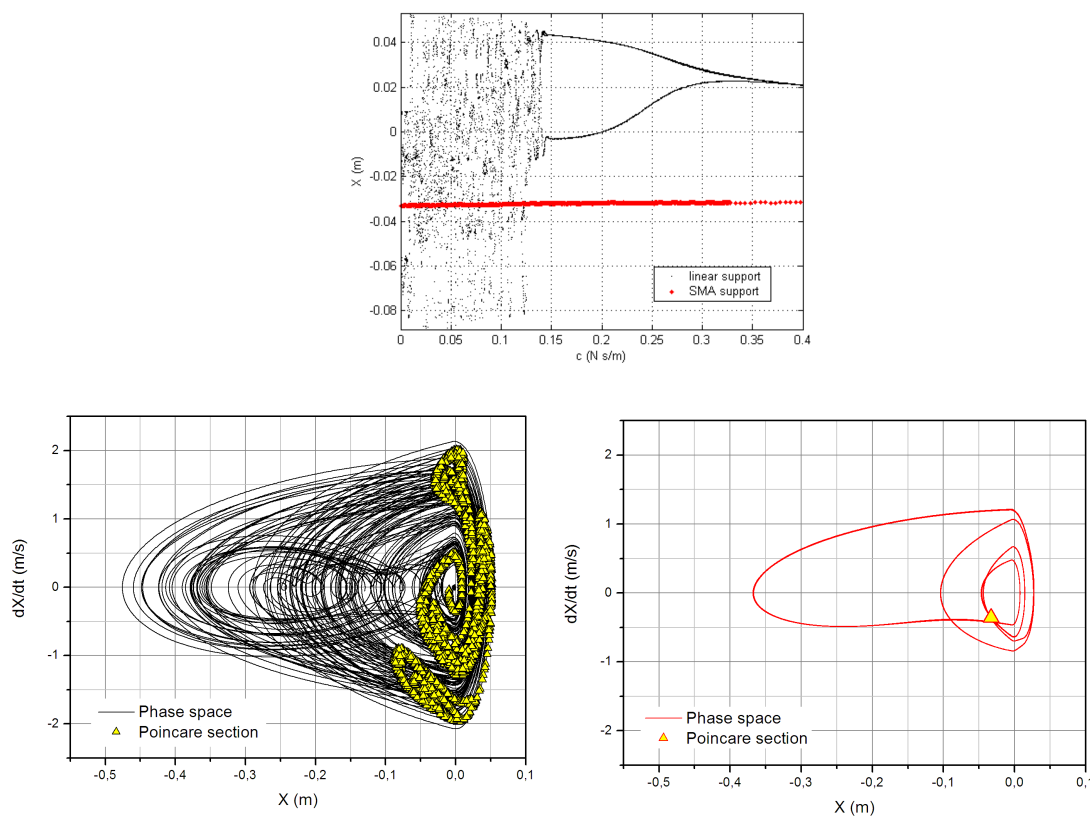


Figure 10 – Non-smooth SMA system.



(a) Linear support model

(b) SMA support model

Figure 11 – Comparison of elastic and SMA response for a non-smooth oscillator.

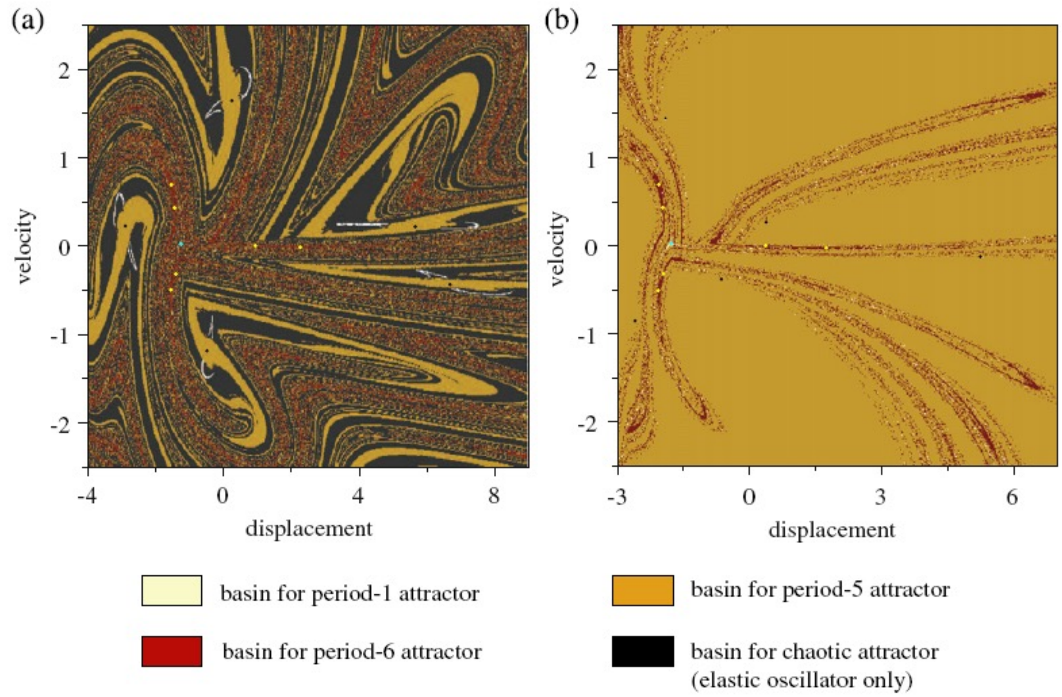


Figure 12 – Basins of attraction for non-smooth systems.

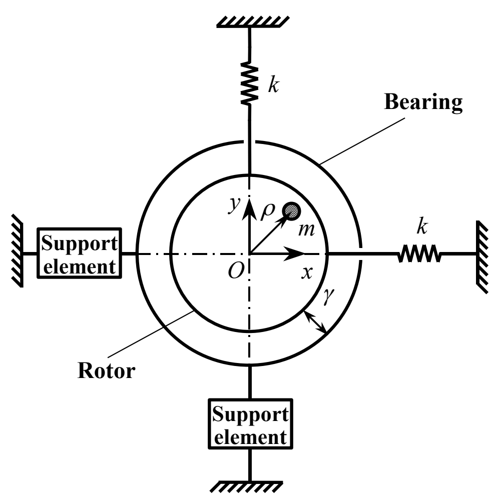


Figure 13 - Rotordynamic nonsmooth system.

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Abstract

The development of the research Project successfully achieves expectations, generating important results from different approaches. In this regard, it is important to highlight joint publications of sub-project participants, showing the mature level of the research. This is due to a strong interaction among different Brazilian Universities (UFRJ, CEFET/RJ, UnB, UFU and UFF) and also among foreign Universities (Texas A&M University, University of Aberdeen, Technological University of Denmark and Dalhousie University). This report highlights the main results of this research effort that includes constitutive modeling, nonlinear dynamics and control of shape memory alloy systems.

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JOURNAL PAPERS – STRICT RELATED TO THE PROJECT

1. "Synergistic Use of Smart Materials for Vibration-Based Energy Harvesting", L.L. Silva, S.A. Oliveira, P.M.C.L. Pacheco & M.A. Savi, European Physical Journal – Special Topics. 2015. ISSN 1951-6355.

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Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

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